Tactile Sensing and Control in Humans and Robotic/Teleoperated Systems

First Year Progress Report
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1. Introduction

Over the last several years, a number of sophisticated robot hands have been developed for laboratory use. However, while such hands approximate the mechanical complexity of human hands, their application in manipulation tasks remains in a primitive stage. Unlike human hands, they rely on minutely programmed task descriptions that are time-consuming to generate and susceptible to unanticipated changes in the task or the immediate environment. This is largely because they cannot use tactile information to detect and respond to changes in an event-driven fashion as humans do. Similarly, teleoperated manipulation systems are slow and difficult to use because the operator does not receive appropriate tactile feedback from the manipulator.

Accordingly, the work described is aimed at advancing our basic understanding of how to acquire, interpret and respond to tactile information and at advancing the state of the art in tactile sensing and information processing for robotic and teleoperated systems. The work involves the development of models of sensor/skin/contact dynamics, algorithms for interpretation of tactile information, and control strategies for responding to tactile events. The following is a summary of the progress that was made in these areas during the first year of the project.

2. Microfabricated Tactile Arrays

Faculty: M. Cutkosky, G. Kovacs
Students: D. Chang, B. Kane

One of the primary objectives of the collaboration among Stanford University, Harvard University and the University of Umea is the development of a conformal tactile sensor invoking biologically motivated mechanical and electrical signal processing schemes. As a step in that direction we have begun development of two high resolution planar tactile arrays. To build such arrays, batch-fabricated silicon sensors are an attractive alternative to expensive, noisy, and labor-intensive hand-assembled sensors.

The first silicon array consists of sensors that measure both the normal and shear components of stress at a surface. This sensor is to be composed of a 20x20 array of multiplexed stress sensing elements spaced at one millimeter intervals and coated with a protective polymeric layer. Each of these elements is a redundantly stabilized peizoresistive microstructure capable of resolving the state of traction stress at the local polymer-substrate interface. As a stress is applied to the structure, the resistance of the polysilicon bridges will change. By measuring the resistance changes in the bridges differentially the normal and shear stresses may be determined. A graphical representation of the polysilicon structure is provided in Figure 1.

The resulting multiplexed stress information is to be sampled digitally and filtered to provide a two dimensional representation of the traction stress applied at the polymer surface. The mechanical sensing array and the amplification circuitry will be fabricated independently. The completed modules may then be connected in a hybrid fashion using standard integrated circuit interconnect technology.

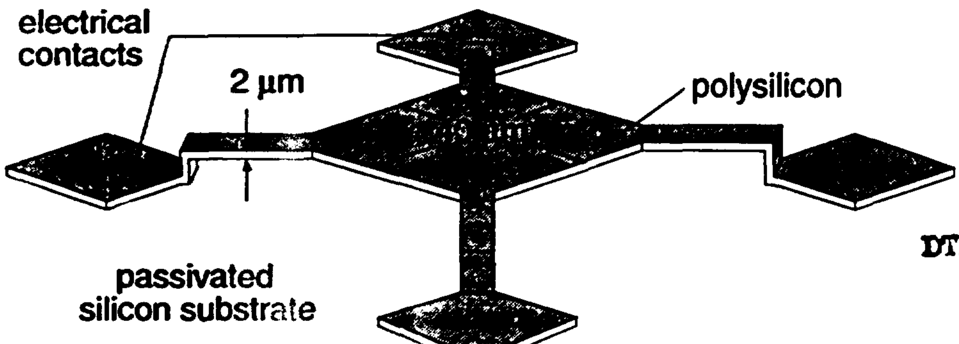

Figure 1: Representative traction sensing element

The second array consists of capacitive elements that sense only the normal component of the surface stress. This functionally simpler design permits row/column scanning so that only $2n$ rather than n^2 bond wires are required for an nxn array. A cross section of a single cell and a plan view of an array are shown in Figures 2a and 2b. Each cell is formed where a beam of Poly2 is suspended over a column of Poly1. The plate gap distance is 0.5 µm, and the dielectric is free air. The capacitive juncture is 50 µm wide and 400 µm deep. Poly 2 rows and Poly 1 columns are elevated from the nitride to minimize parasitic capacitance with the conductive substrate. Aluminum conductors on top of Poly 2 run between neighboring cells and minimize RC time delays as signals travel across the arrays.

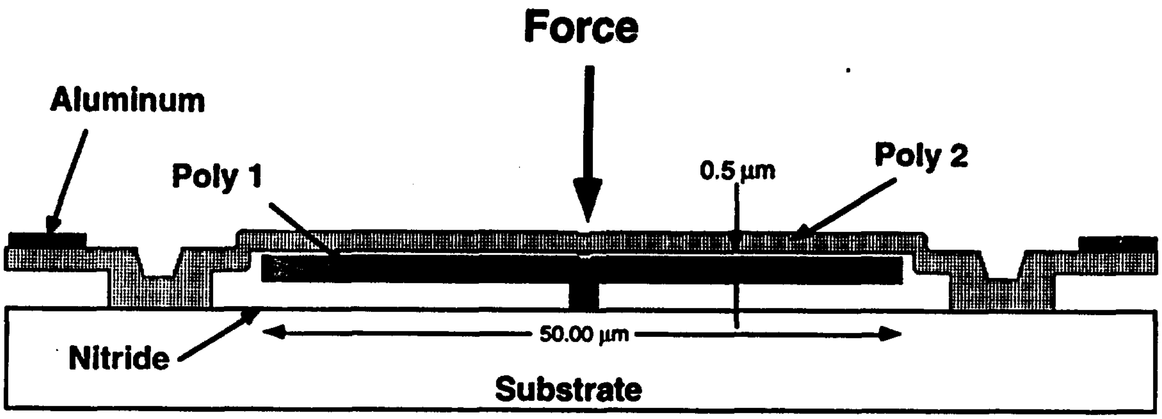

Figure 2a: Cross section of representative capacitive sensing element

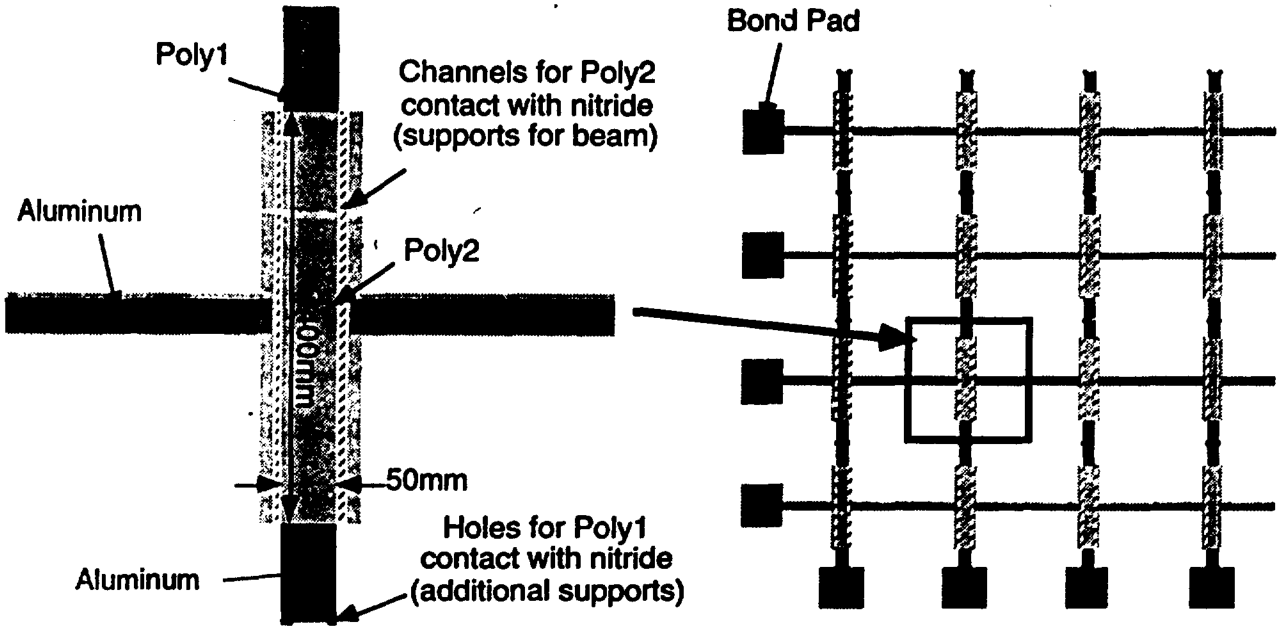

Figure 2b: Plan view of typical element and 4x4 segment of capacitive array

Status:

Lithography masks have been generated for the prototype micro-mechanical structures as well as the amplification and multiplexing circuitry. Fabrication of both the sensors and the circuitry are under way. The Micro Electro-Mechanical Systems (MEMS) process at the Micromachining Center at North Carolina is being used as a foundry. Our designs are to be returned from MCNC in late August 1993. At that time, we will test the external signal processing circuitry and conduct verification and calibration experiments. If these tests are successful, the flat arrays can be mounted onto the sides of an instrumented object for dextrous manipulation experiments with robotic and human fingers. For robotic experiments, the sensors will provide information for manipulation control.

The BiCMOS process at MOSIS Corporation has been utilized as a foundry for fabricating the amplification and multiplexing circuitry for the piezoresistive normal and shear traction array. The circuit design techniques allow for sensitive measurement of the resistance changes in the structure legs. Although the circuit designs are relatively standard they have been implemented in a unique processing architecture which allows quick regression of the traction information. These circuits have been returned and tested with a dummy resistive bridge. Although the MCNC foundry provides quick fabrication of the initial sensor structures, construction of the final sensor array will be completed in the Center for Integrated Systems at Stanford University. Initial design studies are being conducted to develop a silicon dioxide based structure. The proposed structure will have the geometry shown in Figure 3. Device fabrication is expcted to be complete by mid December of 1993.

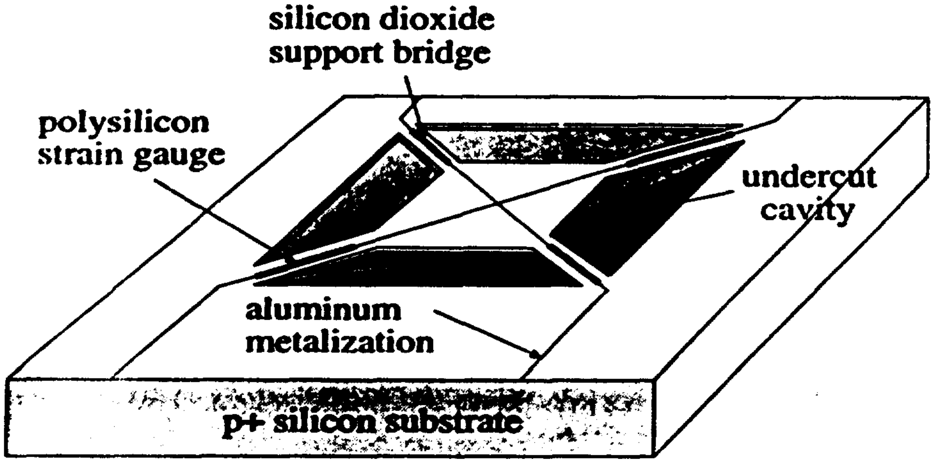

Figure 3: Proposed silicon dioxide traction stress sensing structure to be fabricated at the Center for Integrated Systems.

3. Tactile sensors for human fingerprint characterization

Faculty: R. Howe
Students: D. Pawluk, P. Park, B. Kim

Other tactile sensors have been fabricated using macroscopic technologies at Harvard, including sensors with 8x8 elements using variable capacitance transduction. Efforts are now focused on maximizing signal-to-noise ratio through improved electronics design. In conjunction with this effect, we are converting the two degree-of-freedom manipulator developed for our teleoperated hand system to use as a tactile stimulator. As this application demands superior force control performance, we are now creating an improved impedance controller.

4. Optical Shape Sensor

Faculty: R. Brockett
Students: R. Irie

We have worked on concept verification and construction of a tactile sensor based on measuring the reflectance pattern that exists when infrared light is reflected from the inner layer of a deformable finger. The configuration has infrared detectors and emitters in a finger casing; we wish to determine the contour of the "skin" on the basis of measurements of the internal reflections. To establish the level of performance one can achieve using this idea we constructed a three layer rectangular enclosure from acrylic. A printed circuit board with an emitter and detector was fabricated and placed inside the enclosure. A rubber skin from a glove coated with silver paint was stretched between the two top layers of the enclosure. Using precision positioners, the skin was depressed at various locations and at various depths. Contour plots were generated showing the light intensity versus position at different depths of depression. Near circular isointensity lines were found, confirming our belief that the location and depth of a single depression can be determined on the basis of reflectance.

The second stage of this research involved the construction of a prototype finger using one emitter and 8 detectors. Surface mount technology was required in order to get the desired density of components. A printed circuit board having traces as thin as 7 mil was milled (not photo-etched) for this purpose. The finger case has been constructed from aluminum and is approximately the size of an actual finger (1"x1.75"). Preliminary data has been collected using precision positioners to depress the finger. The contour graphs show a distinctive pattern but we have not yet quantified the performance.

5. Microprobes for human fingertip tissue characterization

Faculty: G. Kovacs

Students: B. Kane

Sensory transduction processes have been successfully studied for many of our senses, but they are not as well understood for the somatic sensations (touch, vibration, temperature, proprioception and pain) in part due to a lack of instrumentation with which to generate precisely controlled, physically localized mechanical stimuli. We have

developed a high-resolution force sensing mechanical microprobe at Stanford for use in the characterization of biological tissues. A microprobe is comprised of a 1 to 2 mm long silicon cantilever beam projecting from a larger supporting silicon substrate. Acting as the variable leg of a Wheatstone bridge circuit, a piezoresistive polysilicon element located at the base of the beam is used to measure the stimulation force applied at the beam tip. The microprobes have been characterized. They exhibit a stable, linear relationship between the stimulation force and the resulting output voltage signal. Stimulation forces up to 0.5 mN have been generated with a measurement resolution of 1.5 μN. These microprobes will be used as the force sensing element of a closed loop feed-back controlled stimulation system used to stimulate human epidermal tissue as well as mechanoreceptive nerve terminals of the rabbit corneal epithelium. A collaborative experimental program is planned between researchers at Stanford University and the University of Umea, Sweden. The intention of this set of experiments is to explore, at a high measurement resolution, the transduction of mechanical information in human skin.

6. Grasp Force Control Using Dynamic Tactile Sensing

Faculty: M. Cutkosky
Students: M. Tremblay

Dynamic tactile sensors, specifically the skin acceleration sensor, have been developed for robotic and teleoperated hands to provide information similar to human fast-acting (FA) mechanoreceptors. Triggering off the "microslip" information provided by these sensors just prior to onset of sliding, a manipulator's force control algorithm can then quickly adjust the grasp force so that no gross sliding occurs. Using such an approach, it is possible for a robot to maintain control of a grasped object, using the minimum necessary grasp force. A second generation of dynamic tactile sensors has been developed at Stanford, along with a modified control scheme for estimating the local coefficient of friction and executing grasp force control. Accelerometers both on and off the finger/object contact area (the middle and side accelerometers, respectively, in Figure 4.) are monitored and compared to provide some immunity to disturbances not associated with microslips. By monitoring the normal and tangential forces at the contact when microslips occur, the hand controller obtains an accurate estimate of the friction coefficient that can then be used during manipulation [Tremblay and Cutkosky 1993].

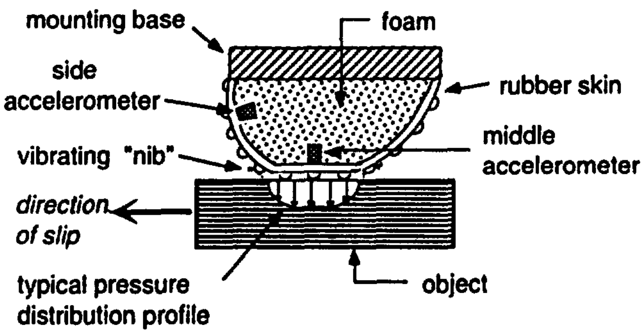

Figure 4: Cross section of incipient slip sensor

7. Contact Transition Control

Faculty M. Cutkosky
Student: H. Hyde

Successful control of contact transitions is an important capability of dextrous manipulators. In recent work we examined several methods for controlling the transition from free motion to constrained motion, with an emphasis on minimizing fingertip load oscillations during the transition. A new approach, based on input command shaping, was developed and compared with several methods described in prior research. The various techniques were evaluated on a one-axis impact testbed. Figure 2 shows a typical run in which the preshaping method is compared with active impact damping. The new input shaping method was found to be comparable, and in some cases superior, to existing methods of contact transition control. Details are provided in [Hyde and Cutkosky 1993].

As an extension of the contact transition research, we are planning several experiments which will examine some of the transitions from stationary to sliding contact. Managing these transitions is also an important capability of robotic manipulators, and can be quite challenging considering the variations in surface texture and friction coefficients that a manipulator might encounter when interacting with objects in its environment. To study these

problems, we have developed a two-axis testbed that can contact and slide along surfaces. Using this testbed and a variety of control techniques and contact surfaces, we hope to gain insight into the problem of sliding transitions. We also intend to develop a controller that can smoothly and effectively manage the transition from stationary contact to sliding contact with a while minimizing fingertip load oscillations.

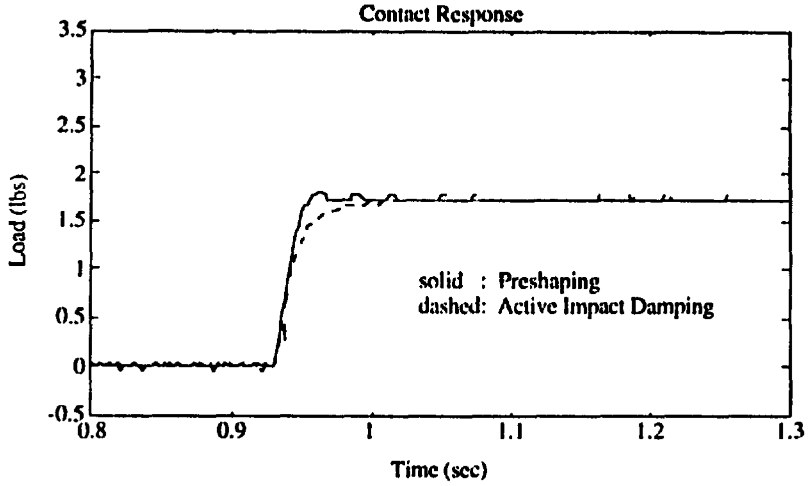

Figure 5: Response of a rubber/foam fingertip to Active Impact Damping and Preshaping controllers.

8. Teleoperation with tactile display

Faculty R. Howe
Students: D. Kontarinis, A. Hajian

We have performed experiments that quantify performance variation with force bandwidth in precision telemanipulation tasks. The experiments use a two fingered teleoperated hand system with finger-level force feedback to perform close-tolerance peg-in-hole insertion. Low-pass filters are used to vary the frequency content of the force feedback signal. Task completion times and error rates decrease as force reflection bandwidth increases. Most of the benefit appears between 2 and 8Hz bandwidth, although some improvement is seen to 32Hz, the highest frequency examined. These experiments also indicate that even low bandwidth force feedback improves the operator's ability to moderate task forces. However, force feedback does not enable the operator to minimize grasp force, since this requires information about the friction at the contact between the grasped object and the slave finger tip. We are now proceeding with design of tactile displays that will convey information about frictional conditions at the slave manipulator to the operator. Details are given in [Howe and Kontarinis 1992].

We have also constructed a prototype tactile display for representing the three-dimensional shape of objects on the human operator's finger tips. This device consists of a 3x3 array of tactile elements on 2mm centers. The actuators are shape memory alloy wires, used in a lever-arm configuration to amplify the range of motion. Each tactor can produce a force of 1.2N and a displacement of 3mm. The present design has a response time of less than 100ms, and improved cooling should increase bandwidth by at least a factor of two. We have tested the display in simple psychophysical experiments, and subjects were able to reliably discriminate edges, corners, and extended area contacts presented on the display. Work is now underway to integrate the tactile display with the force-reflecting teleoperated hand system in our laboratory. Input for the display will come from capacitive tactile array sensors mounted on the slave finger tips. These sensors will measure the shape of grasped objects, and these shapes will be recreated on the operator's finger tips by the tactile display at the master manipulator. Planned experiments will evaluate the display's use in tasks which require discrimination of contact shape for effective control of hand-object kinematics.

9. Motion Control Theory

Faculty: R. Brockett

We have described a mathematical framework for modeling motion control systems and other families of computer controlled devices that are guided by symbol strings as well as analog (real valued) signals. It presents a particular method of organizing the lower level structure of such systems and argues that this method is widely applicable. Because the models used capture important aspects of control and computer engineering relevant to the

real-time performance of symbol/signal systems, they can be used to explore questions involving the joint optimization of instruction set and speed of execution. We have made some comparisons between engineering and biological motion control systems, suggesting that the basic ideas advanced here are consistent with some aspects of motor control in animals. Details are provided in [Brockett 1993].

10. Publications:

[Brockett 1993]
Roger Brockett, "Hybrid Models for Motion Control Systems", Perspectives in Control, H. L. Trentelman and J. C. Willems, Eds.) Burkauser, Amsterdam, 1993 (to appear)

[Howe and Kontarinis 1993]
R. D. Howe and D. Kontarinis, "Task Performance with a Dextrous Teleoperated Hand System," Proc. SPIE vol. 1833: Telemanipulator Technology 1992, Boston, Nov. 15-16, 1992.

[Hyde and Cutkosky 1993]
J. H. Hyde and M. R. Cutkosky, "Contact Transition Control: an Experimental Study," Proceedings of the 1993 IEEE International Conference on Robotics and Automation, May 2-6, Atlanta, GA, pp. 363-368.

[Kontarinis and Howe1993]
D. Kontarinis and R. Howe, "Tactile Display of Contact Shape in Dextrous Manipulation," Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME Winter Annual Meeting, Nov. 28-Dec. 3, 1993 (to appear).

[Tremblay and Cutkosky 1993]
M. R. Tremblay and M. R. Cutkosky, "Estimating Friction Using Incipient Slip Sensing During a Manipulation Task," Proceedings of the 1993 IEEE International Conference on Robotics and Automation, May 2-6, Atlanta, GA, pp. 363-368.